# **Rare species of dark matter** Maxim Pospelov FTPI and U of Minnesota

- Introduction. Difficult spots for direct detection. A. Light dark matter. B. Thermalized dark matter fraction. *Dark matter through multiple collisions.*
- Light dark matter reflected from A. the Sun, B. from cosmic rays. Constraints on scattering cross section.
- Rare species of strongly interacting dark matter. DM flux: "traffic jam" and hydrostatic population
- Signatures: A. Signatures for neutrino detectors: Direct annihilation inside underground neutrino detectors. B. Possible use of underground accelerators: a scheme to search for strongly interacting DM in double collision C. Constraints from the DM detectors at nuclear reactors. D. De-excitations of nuclear isomers. Interesting case of <sup>180</sup>Ta.

## **References and Collaborators**

- New sensitivity to light dark matter via solar reflection (With H. Nie, H. An, J. Pradler, A. Ritz). (2018 PRL, 2021 PRD)
- Acceleration of DM by cosmic rays (With T. Bringmann). 1810.10543 [hep-ph], (2019 PRL)
- Possible use of underground accelerators? (With M. Moore, D. McKeen, D. Morrissey, H. Ramani). 2202.08840[hep-ph]
- Constraints on Dark Matter from Nuclear Reactors. 2402.03431 [hep-ph] (With Y. Ema, A. Ray)
- Constraints on Dark Matter from Nuclear Isomers. 1907.00011 [hep-ph] (With S. Rajendran, H. Ramani). B. Lehnert et al., 1911.07965 [Astro-ph.co], PRL 2020
- I also worked on related topics with A. Berlin, H. Liu.

■ Impressive 2022-24 updates of Direct detection limits by LZ, XenonNT.



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# **Blind areas for direct detection**

1.  $\sim$ MeV scale dark matter: Kin Energy = mv<sup>2</sup>/2  $\sim$  (10<sup>-3</sup>c)<sup>2</sup>(MeV/c<sup>2</sup>) $\sim$ eV. Below the ionization threshold! ( $v < 2*10^{-3}$  c)

2. Strongly-interacting subdominant component of Dark Matter. Thermalizes before reaching the underground lab, Kin energy  $\sim$  kT  $\sim$ 0.03 eV

(Typically cannot be entire DM, but is limited to fraction  $f_{\chi}$ <10<sup>-3</sup>)

Below the ionization threshold!

## **Different strategies to cover blind spots**

1. Develop new technologies that will be sensitive to the sub-eV energy deposition.

2. Explore multiple collisions of DM to fill in "blind spots"



# **Excess background at low energy**

- LZ, Xenon NT, the counting rate is as low as  $\sim$  10 events / ton / year / keV ~ below 10<sup>-4</sup> events/kg/day, With  $E > 0.5$  keV
- Typical counting rates at lowest threshold semiconductor detectors are large, currently plagued by unexplained excess:



Collaborative summary paper based on the results reported at EXCESS 2021

https://arxiv.org/abs/2202.05097

Counting rates in low-threshold semiconductors, at a  $\sim$  few 10 eV electron recoil,  $\sim 10^6$  events/kg/day



### **"Reflected DM": extending the reach of Xe experiments to WIMP scattering on electrons** 2



• Initial kinetic energy  $m_{dm}(v_{dm})^2/2$  with  $v_{dm} \sim 10^{-3}$ c (that has an endpoint at  $\sim 600$ km/sec )can be changed by scattering with electrons,  $v_{el} \sim (2 T_{core}/m_e)^{1/2} \sim up$  to 0.1 c. In particular E<sub>reflected</sub> can become larger than E<sub>ionization</sub>. and XIII NESSEE ON SCALE FROM THE GALACTIC ON SCALE POPULA  $\frac{1}{\sqrt{2}}$  contours denote functions. The thick gray relic density  $\frac{1}{\sqrt{2}}$ indicates a schematic lower limit from stellar energy loss while the  $t = \frac{(1)(2)(2)}{16}$  radius, and the strength of the strength of the strength of the reflection of the reflection of the reflection of the strength of the reflection of the strength of the strength of the strength of the str igy  $m_{dm}(v_{dm})^{-/2}$  with  $v_{dm}^{\sim}$  to c (that has an  $\sigma$ anged by scattering with electrons,  $v_{el} \sim (2 \text{ T}_d)$  $\sum_{\text{reflected}}$  can be come target than  $\sum_{\text{[OIIIZATION]}}$  $\begin{array}{ccc} \sim & 2 & \sqrt{3} & \sqrt{$  $\Gamma$ <sup>o</sup>c (that has an endpoint at  $\sim$ 600  $v_{\text{c}}$  and an endpend to the distributions below  $v_{\text{c}} \sim (2 \text{ T} - \frac{1}{2})^{1/2} \approx 11 \text{ n}$  to beach, r

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• Huge penalty in the flux of "reflected"  $DM \sim 10^{-6} \sim$  solid angle of the Sun  $\Phi_{\rm refl} \sim \frac{\Phi^{\rm halo}}{4} \times$  $\int 4S_g$  $\frac{S_g}{3} \left(\frac{R_{\text{core}}}{1 \text{ A.U.}}\right)^2 \sigma_e n_e^{\text{core}} R_{\text{core}}, \ \ \sigma_e \ll 1 \text{ pb},$  $S_g\left(\frac{R_{\text{scatt}}}{1 \text{ A.U.}}\right)^2$ ,  $\sigma_e \gg 1 \text{ pb.}$ lar Model [26] was used to determine the temperature, For a given cross section *e*, the scattering rate was then  $\sigma_e \ll 1$  pb,  $p \propto 1$  in the next step with velocity shifted accord- $\sigma_e \gg \text{1}$  po.

## **Analogy with Sunyaev-Zeldovich effect**



- CMB photons are upscattered by hot gas in clusters of galaxies. Decrement at low frequency and increase at higher frequency.
- 8 • Solar electrons will do the same to light dark matter. Sun will be seen as a "hot spot" in dark matter.

## **Contact mediator, limits on σ<sub>e</sub>**



### An, Nie, MP, Pradler, Ritz, 2017, 2022

- Large Xe-based detectors improve sensitivity to  $\sigma_e$  through reflected flux. Sensitivity to cross section on electrons down to  $10^{-38}$  cm<sup>2</sup>. Sensitivity to cross section on electrons down to  $10^{56}$  cm<sup>2</sup>.
- Significant fraction of "freeze-out" line for DM abundance is excluded in a simple WIMP model.

## **Massless mediators, limits on σ<sub>e</sub>**



#### An, Nie, MP, Pradler, Ritz, 2021  $X_1, Y_2, Y_3, Y_4, Y_5, Y_6, Y_7, Y_7, Y_8, Y_9, Y_1, Y_2, Y_3, Y_1, Y_2, Y_3, Y_4, Y_5, Y_6, Y_7, Y_7, Y_8, Y_9, Y_1, Y_2, Y_3, Y_4, Y_6, Y_7, Y_7, Y_8, Y_9, Y_1, Y_1, Y_2, Y_3, Y_4, Y_6, Y_7, Y_7, Y_8, Y_9, Y_1, Y_1, Y_2, Y_3, Y_1, Y_1, Y_2, Y_3, Y_4, Y_6, Y_7, Y_7, Y_7,$

- Large Xe-based detectors improve sensitivity to  $\sigma_e$  through reflected flux. electron references and  $\frac{m}{2}$  in the section  $m$ ,  $\frac{m}{2}$  is  $\frac{m}{2}$  and  $\frac{m}{2}$ . **Right partition from the section of**  $\frac{m}{2}$
- Second case, massless mediator = milli-charged dark matter, Xe1T is sensitive to  $Q_{\text{eff}}$  ~ few 10<sup>-10</sup> e.  $\sim$  3000110 case, massiess inculator =  $\min$ -charged dark matter, ACT
- 10 • The results are cross-checked with Stony Brook group (some errors corrected)

## **Light DM accelerated by cosmic rays**

- There is always a small energetic component to DM flux (Bringmann, Pospelov, PRL 2019, others) due to interaction with cosmic rays.
- Typically: MeV DM mass  $\rightarrow$  eV kinetic energy  $\rightarrow$  sub-eV nuclear recoils. No limits for  $\sigma_{\text{nucleon-DM}}$  for DM in the MeV range.
- This is not quite true because there is always an energetic component for DM, not bound to the galaxy. Generated through the very same interaction cross section:  $\sigma_{\gamma}$

 $M$ ain *idea*: Cellisians of  $DM$ Main idea: Collisions of DM with cosmic rays generate sub-*I* omi  $\overline{I}$ <sup>2</sup> *m<sup>i</sup>*  $\overline{\mathbf{a}}$ 1 *±*  $\overline{a}$  $ux$   $Wi$ *m*  $th \sim 10$  $\int$ <sup>*n*</sup> *i*  $\int$  $\overline{a}$ #  $dominant DM flux with  $\sim 100$$ where the + () sign applies for *T >* 2*m<sup>i</sup>* (*T <* 2*mi*). irect detection type recoil direct detection type recoil. *MeV momentum – perfect for* 



## **Resulting limits on WIMP-nucleon scattering**



Spin-independent limits. [Notice the constraint from Miniboone, from measurements of NC nu-p scattering]. Exclusion of  $\sigma$  $= 10^{-29} - 10^{-31}$ cm<sup>2</sup> !

- Scattering on free protons in e.g. Borexino, SNO, SK sre also very constraining e.g. for the spin-dependent scattering.
- (Ema, Sala, Sato had an independent work along the same lines for  $\sigma_e$ )

#### **Updated limits on WIMP-nucleon scattering** wint-nucleon scatte Monte Carlo (MC) simulation method developed in our previous work [27], with nucleon targets replaced by elec-



# **Two blind areas for direct detection**

1.  $\sim$ MeV scale dark matter: Kin Energy = mv<sup>2</sup>/2  $\sim$  (10<sup>-3</sup>c)<sup>2</sup>(MeV/c<sup>2</sup>) $\sim$ eV. Below the ionization threshold!

2. Strongly-interacting subdominant component of Dark Matter. Thermalizes before reaching the underground lab, Kin energy  $\sim$  kT  $\sim$ 0.03 eV

(Typically cannot be entire DM, but is limited to fraction  $f<10^{-3}$ )

Below the ionization threshold!

Nightmare embarrassing scenario

### **Rare species of strongly interacting dark matter**

- Most advanced direct dark matter detection experiments are so far ahead of other probes that we would not be able to distinguish between  $(f_{\gamma} = 1 \text{ and } \sigma = 10^{-47} \text{ cm}^2, \text{ and } e.g. f_{\gamma} = 10^{-3} \text{ and } \sigma = 10^{-44}$  $cm<sup>2</sup>$ )
- Assuming a wide range of  $f_{\gamma}$ , 10<sup>-10</sup> to 1 is reasonable, as it can be broadly consistent with the freeze-out models.
- If  $f_\chi$  << 1 (e.g. 10<sup>-5</sup>) significant blind spots exist for large scattering cross section values (e.g. 10-28 cm2) which can easily arise in models with relatively light mediators. The accumulation and distribution of DM inside astrophysical bodies (most importantly, the Earth) will change.



### **Model realization** concrete model, we consider a dark sector that with a

- **P** Dark photon mediate DM with  $m_A$ ,  $\leq m_\chi$ . the low-energy e $\mathcal{L}_{\text{max}}$  equation  $\mathcal{L}_{\text{max}}$  $\mathcal{L}=-\frac{1}{4}% \sum_{i=1}^{39}\left[ \frac{1}{2}\right] ^{i}\mathcal{L}^{i}$ 4  $(F'_{\mu\nu})^2 - \frac{\epsilon}{2}$ 2  $F'_{\mu\nu}F^{\mu\nu} +$ 1 2  $m_{A^\prime}^2$  $(A'_\mu)$  $\mathcal{E}$  $+ \bar{\chi} (i \gamma^{\mu} D_{\mu} - m_{\chi}) \chi$ , ■ Da  $\mathcal{L}$  $\sim$  2  $\overline{a}$  $m_\chi$ .  $\left(F'_{\mu\nu}\right)^2 - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_{A'}^2 \left(A'_\mu\right)^2$ ⇤<sup>2</sup> [*ch*(*H†*  $\frac{d^2\mu\nu}{dt^2} + \frac{1}{2}m_{A'}^2$  $\left(A'\right)^2$ ⇤<sup>2</sup> *ti*¯ 5*<sup>t</sup>* ⇥ *<sup>h</sup>*
- is the mass of dark photon, *D<sup>µ</sup>* = @*<sup>µ</sup> igdA*<sup>0</sup> Main process:  $\chi \bar{\chi} \rightarrow A'$  $\overline{3}$  $\chi \bar{\chi} \rightarrow A'A'$  with  $A' \rightarrow SM$ <sup>16</sup>⇡<sup>2</sup> ⇥ *<sup>Y</sup>* <sup>2</sup>  $SM$

 $A = \begin{bmatrix} 1 & 1 \end{bmatrix}$ Dark coupling constant of 0.5 and dark matter mass results in the fractional abundance  $\sim$  3 10<sup>-9</sup>. Scattering cross section on nucleons is large, if  $m_A$  is in 10's of MeV lim = 0*.*24 yr<sup>1</sup>. While a  $\Gamma$  $\mathbf c$ cross-section could be obtained from existing SK data possible for *m<sup>A</sup>*<sup>0</sup> *< m* [19] and eciently depletes the Dark coupling constant of 0.3 and dark matter mass of 2.5 GeV on on nucleons is large  $if m_{\theta}$  is in  $10$ 's of MeV ra  $\sigma^{2}$ <sub>2</sub>,  $\sigma^{2}$ <sub>1</sub>, 4<sup>2</sup> section on nucleons is large, if  $m_A$  is in 10's of MeV range!  $H^2$   $\alpha$  *C*  $\alpha$  *C* 

$$
\sigma_{\chi A} = \frac{16\pi Z^2 \alpha \alpha_d \epsilon^2 \mu_{\chi A}^2}{m_{A'}^4}
$$

### **Rare species can be accumulated in large amounts**

When the cross section on nuclei is small, the probability of capture is very small Sivertsson & Edsiö. 2012



When the cross section is large, the maximum capture  $=$  Flux  $*$  $\pi(R_{\text{Earth}})^2 \sim 10^{24}$  /sec for a 10 GeV WIMP. More than 10 order of magnitude enhancement.

#### **Dark matter traffic jam** *Pain II T* = 300 K, *m*gas ⇠ *A* ⇥ GeV and take A ⇠ 30 for rock. tar traffic iam

- Rapid thermalization cross section is expected to be 4<sup>₹</sup>
- Flux conservation:  $v_{in}n_{halo}$  =  $V_{terminal}$   $n_{lab}$ . it to be on the same order of magnitude as the elastic one. • Flux conservation:  $v_{in}n_{halo}$  =
- Terminal sinking velocity is determined by the effective  $\qquad \qquad \blacksquare$ mobility ( $\sim$  inverse cross section) and gravitational forcing and gravitational forcing  $\lim_{n\to\infty}$

$$
v_{\rm term} = \frac{3M_{\chi}gT}{m_{\rm gas}^2n\langle\sigma_t v_{\rm th}^3\rangle}
$$

- Change in velocity from incoming  $\sim 10^7$  cm/s to typical sinking velocity of 10 cm/s results in  $n_{lab}$  $\sim 10^6$  n<sub>halo</sub>. Not visible to DD where  $\alpha$  is the desire for  $\alpha$  is the mass of gas part of  $\beta$ **tion, the number of the number of the number of gas particles,** *the Change m* **velocity from mcomming**  $\alpha$
- At masses  $< 10$  GeV upward flux is important and density goes up.  $\frac{1}{2}$  for the  $\frac{1}{2}$  cross-section scattering cross-section scattering cross-section at  $\frac{1}{2}$

**thermalization**  $\sim$  Incoming particles  $\mathbb{R}^d$  Diffusion biased by  $\text{grad}$  drift A lab for trains **Jam** in Fig. 2 (Left). There are three distinct regimes at play. where the column density is not enough to slow  $\mathcal{N}$ velocity approaches the thermal velocity, the slow down is enhanced leading to a jump to *v*th. Next, for crosssections where vertical velocity drops below *v*th, the adis linearly proportional to the size of the elastic cross section. Finally, once *v*term is reached, there is no further slow down and a flat regime for the density enhancement is achieved. Fig. 2 (Right) shows contours of equal ⌘ in the *<sup>N</sup>* vs *M* plane. ⌘ increases as a function of *<sup>n</sup>* till *<sup>n</sup>* ⇠ 10<sup>30</sup> cm<sup>2</sup> which corresponds to the saturated geometric

ment. As mass of DM, *M* is dialed up, the terminal MP, Rajendran, Ramani 2019 MP, Ramani 2020, Berlin, Liu, MP, Ramani, 2021

## **Density of trapped particles: best mass range = few GeV.**

§ Lowest mass – evaporation, Highest mass – traffic jam, intermediate mass – trapping with almost uniform distribution inside Earth's volume.



- **FIG.** Enhancement of the density can be as high as  $10^{14}$ . (First noted by Farrar and collaborators) **Farrar** and collaborators Earth as a function of mass (*m*) and per-nucleon cross sec-
- 19 **•** "Less is more". Having 1 GeV particle with  $f_\chi = 10^{-5}$  fractional DM abundance may result in  $\sim 10^9/\text{cm}^3$  concentrations, not  $10^{-5}/\text{cm}^3$ . This has to be exploited.  $\sigma$ . Having T Oc v particle with  $I_{\gamma} = I_0$ Consider a beam of nuclei of mass *m<sup>b</sup>* and kinetic en- $\alpha$  *E*<sup>*b*</sup> including  $\alpha$  including  $\alpha$  including  $\alpha$  $p = 0$  is the contract to  $\frac{1}{2}$

**Signature #1: annihilation inside the SK volume**  $\mathbf{P} \mathbf{V}$ ] DM is often searched by its annihilation to  $m$  gum to  $\mathbf{C}$  with subsequent conversion of neutrinos to visible energy inside neutrino telescopes tica Student Edition e propose that DM can be searched with **under the aby Wolfram Mathematica Student Edition** Inside detector volumes in the mass range  $\sim 1$ -5 GeV. the fiducial volume of Super-Kamiokande (red shaded). Each panel shows a specific mass fraction *f*: *f* = 10<sup>10</sup> (top left),

■ Hydrostatic population is built up by incoming DM until it is counterbalanced by the annihilation (we assume s-wave). The distribution over radius is given by Euler eq. (see our papers, + Leane, Smirnov) distribution and Distribution and Distribution and Distribution and Distribution and Distribution and Distributio<br>Textus distribution and Distribution of Distribution of Distribution and Distribution and Distribution and D a  $\alpha$ cleon cross section *n*, and self-annihilation cross sec- $\frac{1}{2}$ et die  $\frac{1}{2}$  $\overline{\overline{\text{over}}}\$  radius is g  $\mathbf{D} = \mathbf{D} \mathbf{D} + \mathbf{D} \mathbf{D} \mathbf{D}$ the by Euler eq. (see our papers,  $+$  Leane, Smirnov)

$$
\frac{\nabla n_{\chi}(r)}{n_{\chi}(r)} + (\kappa + 1)\,\frac{\nabla T(r)}{T(r)} + \frac{m_{\chi}g(r)}{k_{B}T(r)} = 0
$$

§ Annihilation rate inside SK is easily calculable relation *f* / 1*/*h*v*iann(*T* ' *m/*25). Extrapolating this  $\blacksquare$  Ar  $\frac{1}{2}$  denotes the temperature profile of the Earth of the Earth profile of the Earth profil **g** Annihilation rate inside SK is easily calculable  $\ddot{C}$  is equity equal or  $\ddot{C}$ Tute more one to easily eureumore

$$
\Gamma_{\text{ann}}^{\text{SK}} = \langle \sigma v \rangle_{\text{ann}} n_{\chi}^{2}(R_{\oplus}) V_{\text{SK}}
$$

$$
\Gamma_{\text{ann}}^{\text{SK}} = \Gamma_{\text{cap}} \times \frac{V_{\text{SK}} G_{\chi}^{2}(R_{\oplus})}{4 \pi \int_{0}^{R_{\oplus}} r^{2} dr G_{\chi}^{2}(r)} \xrightarrow{G_{\chi} \to 1} \Gamma_{\text{cap}} \times \frac{V_{\text{SK}}}{V_{\oplus}},
$$

## **Similar to di-nucleon decay signatures**

- Constraints from a possible background-free search
- Lower masses evaporate, heavier masses sink too much.



Assuming a background free search with  $2m<sub>r</sub>$ invariant mass energy release. In many models: strong similarity to  $nn \rightarrow \pi^0 \pi^0$  search by SK (background free,  $\sim 0.1$ signal efficiency).

#### **Constraints on dark photon mediated DM** concrete model, we consider a dark sector that with a **Constraints on dark photon mediat** laboration has shown that in certain decay channels,  $\mathbf{e}$ alated

■ Dark photon mediate DM with  $m_A$ ,  $\le m_\chi$ . the low-energy e $\mathcal{L}_{\text{max}}$  equation  $\mathcal{L}_{\text{max}}$  $\mathcal{L}=-\frac{1}{4}% \sum_{i=1}^{39}\left[ \frac{1}{2}\right] ^{i}\mathcal{L}^{i}$ 4  $(F'_{\mu\nu})^2 - \frac{\epsilon}{2}$ 2  $F'_{\mu\nu}F^{\mu\nu} +$ 1 2  $m_{A^\prime}^2$  $(A'_\mu)$  $\mathcal{E}$  $+ \bar{\chi} (i \gamma^{\mu} D_{\mu} - m_{\chi}) \chi$  ,  $\blacksquare$  Dark photon n  $\mathbf{B}$ ased on these considerations, we derive an anticipated and an anticipated and anticipated and anticipated and  $\mathbf{B}$  $\mathcal{L} = -\frac{1}{4} \left( F'_{\mu\nu} \right)^2 - \frac{1}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_{A'}^2 \left( A'_{\mu} \right)^2$ tions that the annihilation final state allows for a simiis the mass of data photon,  $\frac{1}{2}$   $\frac$  $+ \bar{\chi} (i \gamma^{\mu} D_{\mu} - m_{\chi}) \chi \, ,$ 



*<sup>µ</sup>*, and *g<sup>d</sup>* ⌘  $\chi \bar{\chi} \to A'A'$  with  $A' \to SM$ 

*A*<sup>0</sup> *GeV* results in the fractional **bundance** *for moderate bark coupling constant of 0.3* abundance  $\sim$  3 10<sup>-9</sup>. New parameter space covered.

22  $\mathbb{Z}_{\infty}$   $\left\{\n\begin{array}{c}\n\alpha_d = 0.3 \\
m_u = 2.5 \text{ GeV}\n\end{array}\n\right\}$  For heavier than 5 GeV

## **Signature # 2: Using underground accelerators to "accelerate" dark matter**

- Some of the underground Labs that host Dark Matter detectors, also have nuclear accelerators (LUNA, JUNA) for a completely different purpose: studies of nuclear reactions.
- We propose to couple nuclear accelerators and dark matter detectors: accelerated protons (or other nuclei) can strike DM particles that can subsequently be detected with a nearby detector.



23 ■ This is going to be relevant for models with large DM-nuclear cross section where A. interaction is enhanced, B. density is enhanced. ✓*µ<sup>N</sup>* ◆<sup>2</sup>  $I$  DM to protons and neutrons and neut anceg, B. gensity is ennar in Eq. (17). This result can also be generalized to low-

### **Spectrum of recoil**

Energy of nuclei in the detector after experiencing collision with the accelerated DM.



FIG. 3. Maximum nuclear target recoil energies  $E_R^{\text{max}}$  for dark matter upscattered by beams of protons (left) or carbon (right) with kinetic energies  $E_b = 0.4$  MeV (solid) and  $E_b = 1.0$  MeV (dashed) for a selection of target nuclei.

Energy of accelerator is  $\sim$  MeV, and given that the thresholds in many detectors are keV and lower, this detection scheme is realistic.  $\lambda$  *L*(*C*<sub>c</sub>) and  $\lambda$  and  $\lambda$  *D* w  $\lambda$ <sub>1</sub>,

See details in M. Moore et al, 2022. measured rate of DM scattering in the detector is

### **Possible new reach in the parameter space**

While 100% fraction of these DM particles is excluded by combination of ballon  $+$  underground experiments (gray area), the accelerator+detector scheme is sensitive to small  $f_{\gamma}$ .



This is a promising scheme that can be tried without additional enormous investment, with existing accelerators (LUNA, JUNA)

### **Signature #3: Nuclear reactors as beam dumps**

- Commercial reactors produce over  $10^{20}$  neutrons/sec. It is a source of anti-neutrinos, and can also be viewed as a neutron beam dump.
- Recently (last  $O(5)$  years), there has been explosion of efforts to detect coherent nucleus-neutrino scattering (CEvNs): i.e. direct detection style detectors are brought to O(20-30m) proximity to reactor cores. Importantly, these detectors are achieving low counting rates (e.g. CONUS collaboration).
- If there is a "bath" of thermalized DM particles, fast neutron scattering will create velocitized DM,  $\chi + n \rightarrow \chi_E + n$ .
- 26 Ema, MP, Ray, 2024, reanalyzed the results of the CEvNs searches using CONUS experiment, and translated it to constraints on GeV dark matter.

### **Constraints on upscattering of DM**



27  $f(x) = \frac{1}{2} \int_0^1 \frac{1}{e^{-x}} \, dx$  region of interest depends both on the detectors and di re derived for spin-dependent scattering. No new limit subscript "eelectron-equivalent" standards for the collected charge of the collected charge of the collected charge output is linear that the collected charge of the collected charge of the collected charge of the collecte ent case, as iarge amount o **)**M  $\epsilon$  $\frac{1}{1}$ *a* energy at CONUS detector to de complete the constraints on the CONUS experiment. Note that the CONUS experiment. Note that, even the CO Novel limits are derived for spin-dependent scattering. No new limits for  $\mathbf{r}$  contribution on large regions of chialding (existing of spin-independent case, as large amount of shielding (over 6m of concrete) leads to suppression of DM energy at CONUS detector section of the SI case is the SI case is the ship of ship the ship of ship the search in the search was a comme location. *Motivates experiments at research reactors with less shielding.* 

## **Signature # 4: DM-catalyzed quenching of nuclear isomers**

Tantalum180m level structure



- Lifetime of the 9- level exceeds  $10^{17}$  years (not established yet)  $\mathcal{L}$ coupling in  $\{t\}$  $\sum_{i=1}^n$
- bundance is not all that small  $(0.01\%)$  $\sigma$  and  $\sigma$  is not an and sinding  $\sigma$ .  $\sigma$  is  $\sigma$ . • Natural abundance is not all that small,  $0.01\%$ .

#### **DM** is a source of large recoil **momentum → Enhancement of decay a** and **momentum → Enh** <sup>180</sup>*<sup>m</sup>*Ta (*J* = 9) has never been observed to decay

- **Momentum transfer k mediated in** scale, suppression for large *L* can increase the lifetime the order of decaving energy e g *|J<sup>f</sup> Ji|* (or sometimes by *|J<sup>f</sup> Ji|* + 1, depending on  $\Omega$   $\alpha$  *R* transitions is smally on • Momentum transfer k mediated in the  $\gamma$ ,  $\beta$  transitions is small: on support **E7** the only other excited state the order of decaying energy, e.g. 100 keV.
- $\sqrt{m}$  and  $\sqrt{m}$  the type of particle transition and matching of particle particle particle parameters.  $i_{\text{Ruclear}}$  k)  $\sim 10^{-3}$ . Enters in the HUGE power in the rate,  $f_{\rm{max}}$  1  $\sqrt{24}$  (1 0  $\sqrt{214}$  $(R_{\text{nuclear}} k)^{2\Delta L} \sim (10^{-3})^{14}.$ isomer in nature - it occurs with a yield of 0*.*011% in nat-•  $(R_{\text{nuclear}} k) \sim 10^{-3}$ . Enters in the HUGE power in the rate,
- Dork mottor is rore ato ato but it <u>Dank</u> matter is fare on one of  $\theta$  and  $\theta$ easily Kinematic suppression by  $(R + \lambda)^{2\Delta L}$  is gone  $d$  down-substitute the decay of the decay of the decay of the ground  $\sum_{n=1}^{\infty}$ • Dark matter is rare etc etc – but it carries large k!  $k \sim / R_{\text{nuclear}}$ easily. Kinematic suppression by  $(R_{\text{nuclear}} / \lambda)^{2\Delta L}$  is gone.



# **Interesting candidate isomers**



<sup>a</sup> Hindrance factors for Lu and Hf derived from the observed half-lifes.

- Tantalum 180m is naturally occurring. Non-radioactive. Provides the safest opportunity.  $t_{\text{untrivial}}$  from  $t_{\text{untrivial}}$  comes  $t_{\text{untrivial}}$  and  $t_{\text{untrivial}}$
- First searches have been performed, but there is a sustained interest to this element from the nuclear physics community. • First searches have been perform mular to ans citation from the own right to estimate the total more accurate to  $\mathbf{r}$  accurately result of  $\mathbf{r}$ i, but there is a sustained  $\delta$ <sup>1</sup> $\alpha$

# Experimental search



- DM induces de-excitation of Ta180m down to the ground state.  $\eta$ ivi muutts ut-tathanon of tatoom uown io int ground sc
	- Ta180gs decays within a few hours to W and Hf. These decays produce 103.5 and 93.3 keV gammas.
	- Search of these gammas above the background in the old data from HADES lab produced upper limits on DM-induced deexcitation of Ta180m.  $T_{1/2}$  > 1.3 10<sup>14</sup> yr

#### **Experimental constraints** no 39.5 keV (1980) - 199.5 keV (199.5 keV (1  $\mathbf{v}$ Majorana Demonstrator's Search for Neutrinoless <u>Donou anno</u>



Combined Constraints

- Left: constraints on strongly-interaction limits  $\sum_{n=26}^{\infty}$  $10^{-4}$  fraction of the total DM abundance.  $\frac{10}{10^{-28}}$ to XQC are covered. • Left: constraints on strongly-inte $\sum_{n=26}^{\infty}$ non-orobiation of the total Div tive to  $\alpha$  defended defined definitions to the 180Ta first excited de-excited de-excited definitions to the 180Ta first excited definitions of  $\alpha$  $\overline{2}$  to XOC are covered  $f(x) = \frac{1}{2} \int_0^1 f(x) \, dx$
- Right: constraints on inelastic da<sup>n matter</sup> or  $\sum_{n=1}^{\infty}$  and  $C_{\text{on}_{\text{St}_\text{right}}}$ are covered.  $\sim$  Kight. Constraints on inclusi are covered.
- $\bullet$  Bulk Ta can be used to "accelera • Bulk Ta can be used to "accelera..... [37] J. R. de Laeter and N. Bukilic, Isotope abundance of

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• New experimental study by Majorana: 2306.01965 G. Mathews, Reanalysis of the (*j* = 5) state at 592 kev 025801 (2005). la10rana: 2306.01965  $\mathcal{S}$  $\frac{2206}{2206}$  01065 density of *fb*O*m*  $\alpha$  *fDD*  $\alpha$ 



# Conclusions

- *There are important "difficult corners" in direct detection. For light dark matter below few MeV best limits come from Xenon+ solar DM.*
- Interesting physics can result from *rare species of DM*, as their elastic cross sections can be very sizeable resulting in enhanced population inside the Earth (traffic jam and hydrostatic population).
- The diversity of DM models creates a diversity of experimental signatures – now it is the right time to explore them, as much investment is made into direct detection of dark matter.
- § Signature 1: direct annihilation inside the neutrino detectors (strong constraints from SK).
- Signature 2: nuclear accelerators to up-scatter DM and detect recoil.
- Signature 3: DM experiments at nuclear reactors can be used.
- 33 ■ Signature 4: nuclear isomer de-excitation is catalyzed. Ta180 is a very attractive candidate. No decay (or DM-induced de-excitation) detected thus far.